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TECHNICAL NOTE 2575

A FLIGHT INVESTIGATION OF THE EFFECT OF CENTER-OF-GRAVITY

LOCATION ON GUST LOADS

By Jack Funk and Earle T. Binckley

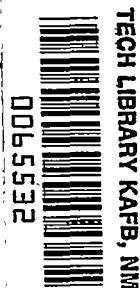
Langley Aeronautical Laboratory
Langley Field, Va.



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A FLIGHT INVESTIGATION OF THE EFFECT OF CENTER-OF-GRAVITY

LOCATION ON GUST LOADS

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SUMMARY

Two jet-propelled airplanes were flown in rough air to investigate the effects of center-of-gravity location on gust loads. Data were obtained at centers of gravity of 20.9 and 27.5 percent mean aerodynamic chord for incremental load factor up to $1g$. The results indicate that a 6.6-percent forward movement of center of gravity decreases the gust loads by approximately 10 percent. The most frequently occurring value of gust gradient distance taken herein as the distance from $1g$ to peak acceleration was 17.5 chords. Calculations of the change in normal acceleration for a center-of-gravity movement from 20.9 to 27.5 percent mean aerodynamic chord for a single triangular gust having a gradient distance of 17.5 chords were in good agreement with the test results.

INTRODUCTION

One of the problems connected with the design of airplanes and their operation in rough air is the effect of the airplane longitudinal stability characteristics on gust loads. Theoretical investigations of this problem (references 1 to 6) indicate a reduction in gust loads with increased static longitudinal stability. However, these investigations made certain simplifying assumptions, and calculations were confined to single gusts of particular shapes. Appreciable differences were noted in the calculated normal-acceleration increments which depended upon the particular simplifying assumptions made and the gust shape used in the calculation. Because of these discrepancies, the prediction of the effects of longitudinal stability by these methods is somewhat in doubt.

In order to obtain an indication from flight tests of the effect of longitudinal stability on gust loads, a cooperative flight investigation was undertaken by the NACA and the All-Weather Flying Division of the U. S. Air Force. Since calculations and gust-tunnel tests (reference 6) indicated that the center-of-gravity location has a greater effect on gust loads than other parameters such as tail length and tail volume and

because of the difficulties involved in varying the other parameters in flight, a flight investigation was undertaken to study the effect of the center-of-gravity location on gust loads.

This paper presents the results of the flight tests with some calculated values for comparison. A statistical analysis was used in evaluating flight test data obtained in continuously rough air and the results therefore include the effect of a sequence of gusts of varying shapes. The calculated values were confined to single gusts of triangular shape because of complexity of calculation for a sequence of gusts on the motion of the airplane.

After conducting these tests, it was found that similar flight tests were made by Hoene (reference 7). The results indicate that, as with the present tests, a forward movement of the center of gravity decreased the gust loads. These tests were conducted with two German airplane types having maximum flight speeds of approximately 180 miles per hour. The present tests were made at higher Mach numbers and wing loading than the tests of reference 7.

APPARATUS

Two jet-propelled airplanes of the same type were used in the investigation. A three-view drawing of the airplane is shown in figure 1 and the pertinent characteristics of each airplane are given in table I.

The following instruments were installed in each airplane to obtain data on the gust loads:

- (1) NACA air-damped recording accelerometer
- (2) NACA airspeed-altitude recorder
- (3) NACA 1-second interval timer

The recording accelerometer had a natural vane frequency of 19 cycles per second and was adjusted for a damping coefficient of 0.7 of critical for standard sea-level conditions. The recorder had a range 4 to -2 g with a vertical trace deflection of 2 inches. The instrument was mounted in the pilot's compartment, approximately $5\frac{1}{2}$ feet forward of the normal center of gravity of the airplane. This location was the closest to the center of gravity of the airplane that was accessible.

The airspeed-altitude recorder was mounted in the nose armament compartment along with the power supply and interval timer. The

total-pressure tube for the airspeed was located below the nose of the airplane forward of the nose wheel. The static pressure for both airspeed and altitude was obtained from the service system of the airplane.

Both instruments were supplied with film magazines having a 50-foot capacity and operating at a film speed of $1/4$ inch per second.

METHOD AND TESTS

The test method consisted of comparing the loads measured in side-by-side flight through clear-air turbulence on two airplanes which differed in center-of-gravity location. As a control, tests were also made with both airplanes having nearly the same center-of-gravity location to check the reliability of the procedure. Cumulative frequency distributions of the magnitude of the measured accelerations were compared on the basis that the difference would be due entirely to the difference in the center-of-gravity locations of the test airplanes.

Twenty-four flights in all were made. Twelve flights were made with center-of-gravity locations of 20.9 and 27.5 percent mean aerodynamic chord, and twelve flights were made with the center-of-gravity locations of 23.0 and 24.9 percent mean aerodynamic chord. Each flight consisted of four runs, two each at 200 miles per hour and 450 miles per hour at an altitude of approximately 1500 feet above terrain. Pilot assignments and the order of high- and low-speed runs were varied to eliminate any consistent combination of conditions that might affect the results. In order to minimize the influence of the pilots on the results, the pilots were instructed to use a minimum of control. Any corrective control necessary to maintain proper airspeed and altitude was made slowly.

Due to safety considerations, the fuselage dive brakes of the airplanes were lowered for the runs at 200 miles per hour in order to allow for an increased engine power setting. Wind-tunnel tests indicate that lowering the dive brakes resulted in no appreciable changes in static longitudinal stability. Measurements of center-of-gravity location were made for the take-off weight for each flight condition. Center-of-gravity travel with fuel load based on these measurements is given in figure 2.

RESULTS

The accelerometer records were evaluated to obtain the magnitude of all acceleration increments above 0.2 g for the 200-mile-per-hour runs and above 0.4 g for the 450-mile-per-hour runs. These thresholds correspond to approximately 4-foot-per-second effective gust velocity

for both speeds. The evaluation was confined to a single maximum or minimum between any two consecutive intersections of the record line with the 1g reference. The airspeed-altitude records were evaluated to obtain an average value of airspeed and altitude for each run from which the total flight distance in air miles was computed.

Since the recording accelerometer was not mounted at the center of gravity, a correction had to be applied to the measured accelerations for the effects of the angular accelerations of the airplane. This correction was made on the assumption that the location of the aerodynamic center of the airplane corresponds to the location of the static-stability neutral point. Even though the accelerations of the center of gravity obtained in this manner are only approximate, an analysis (see appendix A) indicates that the ratio of the accelerations of the two test center-of-gravity locations is insensitive to the location of the lift vector, and that the preceding assumption results in an error of less than 1 percent.

The accelerations obtained for each set of tests were corrected to a standard weight of 10,750 pounds on the basis that the acceleration is inversely proportional to the airplane weight. These data were then sorted into frequency distributions in intervals of 0.05 g for the 200-mile-per-hour tests and 0.10 g for the 450-mile-per-hour tests for each airplane. These distributions and the flight miles for each test condition are given in tables II and III. Cumulative frequency distributions were obtained from the data of tables II and III by summing the frequency distributions. The plots of figures 3 and 4 were obtained by dividing the cumulative frequency distributions into the total flight miles. The figures show the average flight miles to exceed a given acceleration increment.

DISCUSSION

The results of the tests with nearly the same center-of-gravity locations (23.0 and 24.9 percent mean aerodynamic chord (fig. 3)) indicate that both airplanes have essentially the same gust experience. It is therefore concluded that side-by-side test flights of the present type and coverage are sufficient to insure substantial equivalent over-all gust experience.

The results of the tests with center-of-gravity locations of 20.9 and 27.5 percent (fig. 4) show an approximate 10-percent difference in the acceleration exceeded once on the average in a given flight distance. The tests at the forward center-of-gravity location gave the lower accelerations. Since the gust experience can be assumed essentially the same it is concluded that the forward movement of the center of gravity from 27.5 to 20.9 percent mean aerodynamic chord resulted in an over-all reduction of 10 percent in the airplane normal accelerations.

For comparison with the experimental results shown in figure 4, calculations were made of the effect of longitudinal stick-fixed stability on gust loads by the method of reference 5. Acceleration ratios $\Delta n/\Delta n_s$ (where Δn_s is the acceleration computed by the sharp-edge-gust equation, reference 6, p. 4) were calculated for triangular gust shapes having various gradients. The results of these calculations for center-of-gravity locations of 20.9 and 27.5 percent mean aerodynamic chord are shown in figure 5 as a function of gradient distance. The results of the calculation indicate a 3-percent difference in the acceleration ratio for gradient distances of 5 chords increasing to 21 percent for gradient distances of 30 chords.

In order to make a comparison between the experimental and calculated values it is necessary to obtain the most frequently occurring gust gradient distance for the test results. The gradient distances according to the usual definition could not be evaluated from the experimental data which were taken in the repeated gust condition. Therefore, it was assumed that the distance traveled while undergoing a change of acceleration from 1 g to peak acceleration was a measure of the gust gradient distance. Data from several flights were evaluated to obtain values of this parameter. The frequency distribution of the values of gust gradient distance thus obtained is shown in figure 6 and shows that the most frequent distance from 1 g to peak acceleration is 17.5 chords. The difference in the calculated acceleration ratios for the two center-of-gravity locations for 17.5 chords is 11 percent, which is in good agreement with the flight test results. The agreement between test results and calculations in the present case suggests that stick-fixed calculations for single gusts may be adequate for the estimation of flight loads in repeated gusts.

CONCLUSIONS

A flight investigation of two jet-propelled airplanes to determine the effect of center-of-gravity location on gust loads has shown that a forward movement of the center of gravity causes a decrease in the gust loads. The results indicated approximately a 10-percent reduction in loads for a forward movement of the center-of-gravity location of 6.6 percent mean aerodynamic chord. Calculations for single triangular gusts assuming stick-fixed conditions were in good agreement with the experimental results.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., September 4, 1951

APPENDIX A

CORRECTION FOR ACCELERATION MEASUREMENTS DUE TO PITCHING

MOTION OF AIRPLANE

Since the recording accelerometer could not be mounted at the center of gravity of the airplane, the measured acceleration for the component of angular acceleration due to pitching motions had to be corrected. This correction was made on the assumption that the aerodynamic center of the whole airplane was located at the stick-fixed static neutral point.

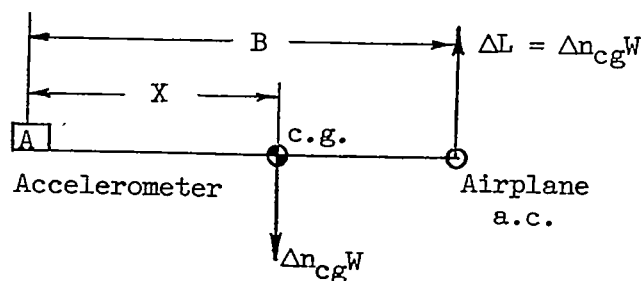
The following symbols are used in the derivation of the correction factor:

M	pitching moment about center of gravity
Δn_{cg}	normal-acceleration increment of center of gravity, g
Δn_θ	linear component of angular acceleration
Δn_A	acceleration increment of point A
B	distance from recording accelerometer to center of lift, feet
X	distance from recording accelerometer to center of gravity, feet
I_y	mass moment of inertia of airplane about center of gravity in pitch, slug-feet ²
$\ddot{\theta}$	angular acceleration

The angular acceleration of the airplane is related to the pitching moment by the familiar equation

$$\ddot{\theta} = \frac{M}{I_y} \quad (A1)$$

From the sketch,



it can be seen that the pitching moment about the center of gravity is given by

$$M = \Delta n_{cg} W(X - B) \quad (A2)$$

Combining equations (A1) and (A2) gives

$$\ddot{\theta} = \frac{\Delta n_{cg} W(X - B)}{I_y} \quad (A3)$$

The linear component of the angular acceleration at point A from equation (A3) is

$$\Delta n_{\theta} = \Delta n_{cg} \frac{W}{I_y} (X^2 - BX) \quad (A4)$$

The acceleration of point A is due to the combined rotational and translational motion given by the equation

$$\Delta n_A = \Delta n_{cg} + \Delta n_{cg} \frac{W}{I_y g} (X^2 - BX) \quad (A5)$$

from which

$$\Delta n_{cg} = \frac{\Delta n_A}{1 + \frac{W}{I_y g} (X^2 - BX)} \quad (A6)$$

For the flight tests at 20.9 and 27.5 percent mean aerodynamic chord, $X_1 = 4.9$ feet, $X_2 = 5.4$ feet, $W = 10,750$ pounds, $I_y = 15,300$ slug-feet³, and $B = 5.8$ feet (where the subscripts 1 and 2 refer to the forward and rearward center-of-gravity locations, respectively), the following correction factors are given:

$$(\Delta n_{cg})_1 = 1.11 \Delta n_{A1}$$

$$(\Delta n_{cg})_2 = 1.05 \Delta n_{A2}$$

The preceding correction was derived on the assumption that the aerodynamic center of the airplane was at the stick-fixed static neutral point in the gust condition. Actually the aerodynamic center changes in the gust condition. Some calculations were made to determine the effects of such a change on the difference between the acceleration

frequency distribution for the test at centers of gravity of 20.9 and 27.5 percent mean aerodynamic chord. The ratio of the acceleration for the forward center of gravity to the rearward center of gravity obtained from equation (A5) by substituting the appropriate values is given by

$$\frac{(\Delta n_{cg})_1}{(\Delta n_{cg})_2} = \frac{(\Delta n_A)_1}{(\Delta n_A)_2} \frac{1.63 - 0.117B}{1.52 - 0.107B} \quad (A7)$$

It can be seen from equation (A7) that the ratio of the accelerations is only slightly affected by the position of the lift vector. A change of ± 5 feet from the assumed location would only cause a 1.8-percent change in the ratio of acceleration for the two center-of-gravity locations. Any reasonable change in the location of the lift vector can thus be seen to have a negligible effect on the present results.

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TABLE I
AIRPLANE CHARACTERISTICS

Item	Airplane I	Airplane II
Mean aerodynamic chord, feet	6.7	6.7
Slope of lift curve, for incompressible flow, per radian . . .	4.7	4.7
Wing area, square feet	237	237
Moment of inertia I_y , slug-feet ²	15,300	15,300
Normal center-of-gravity location		
Average test weight	10,711	10,566
Center-of-gravity location, percent M.A.C.	23.0	24.9
Shifted center-of-gravity location		
Average test weight	10,936	10,610
Center-of-gravity location, percent M.A.C.	20.9	27.5



TABLE II
FREQUENCY DISTRIBUTION OF ACCELERATIONS FOR
200-MILE-PER-HOUR FLIGHT SPEED

Class interval (g)	Airplane and center-of-gravity location			
	Airplane I (23.0)	Airplane II (24.9)	Airplane I (20.9)	Airplane II (27.5)
0.20-0.25	527	642	728	623
.25- .30	334	278	418	340
.30- .35	89	144	128	172
.35- .40	47	52	51	76
.40- .45	25	33	18	22
.45- .50	12	9	3	10
.50- .55	4	5	4	3
.55- .60	0	1	1	3
.60- .65	1	---	1	1
Total flight miles:	444.7	440.7	455.5	451.7



TABLE III
FREQUENCY DISTRIBUTION OF ACCELERATION FOR
450-MILE-PER-HOUR FLIGHT SPEED

Class interval, Δn_g	Airplane and center-of-gravity location			
	Airplane I (23.0)	Airplane II (24.9)	Airplane I (20.9)	Airplane II (27.5)
0.40-0.50	778	781	888	935
.50- .60	392	370	446	480
.60- .70	188	165	269	275
.70- .80	75	84	125	163
.80- .90	39	36	69	80
1.00-1.10	7	6	9	22
1.10-1.20	6	6	3	9
1.20-1.30	0	2	1	4
1.30-1.40	3	---	3	1
1.40-1.50	0	---	---	1
1.50-1.60	1	---	---	1
Total flight miles:	461.2	463.6	456.8	455.2



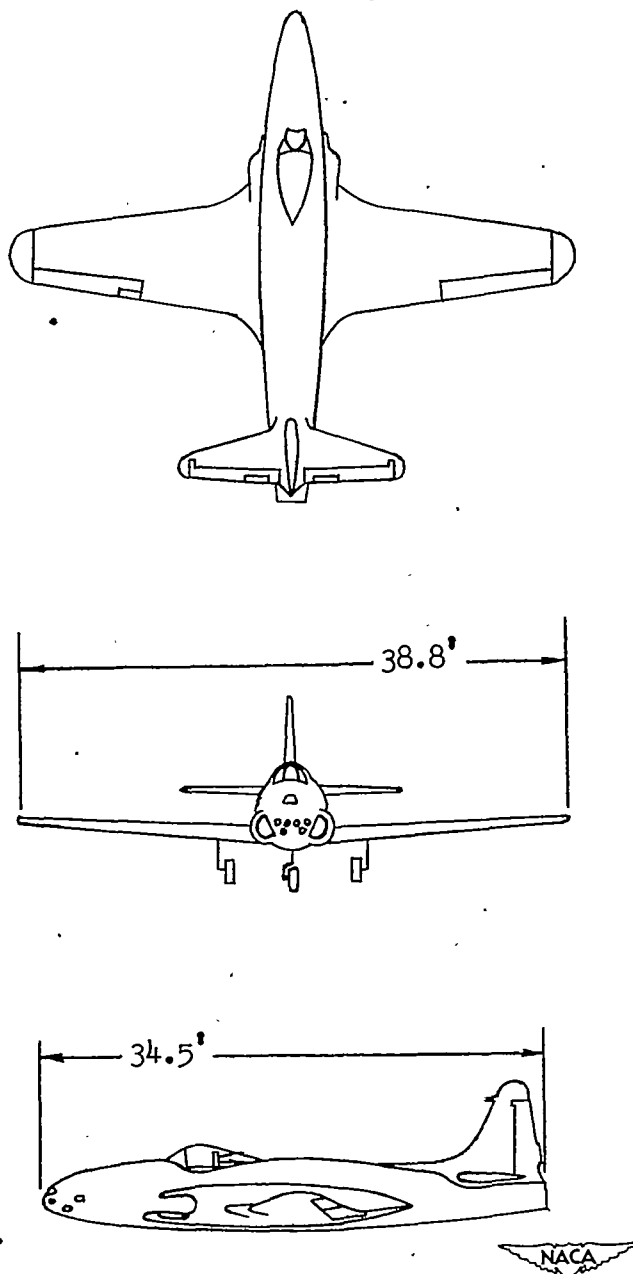


Figure 1.- Three-view drawing of test airplane.

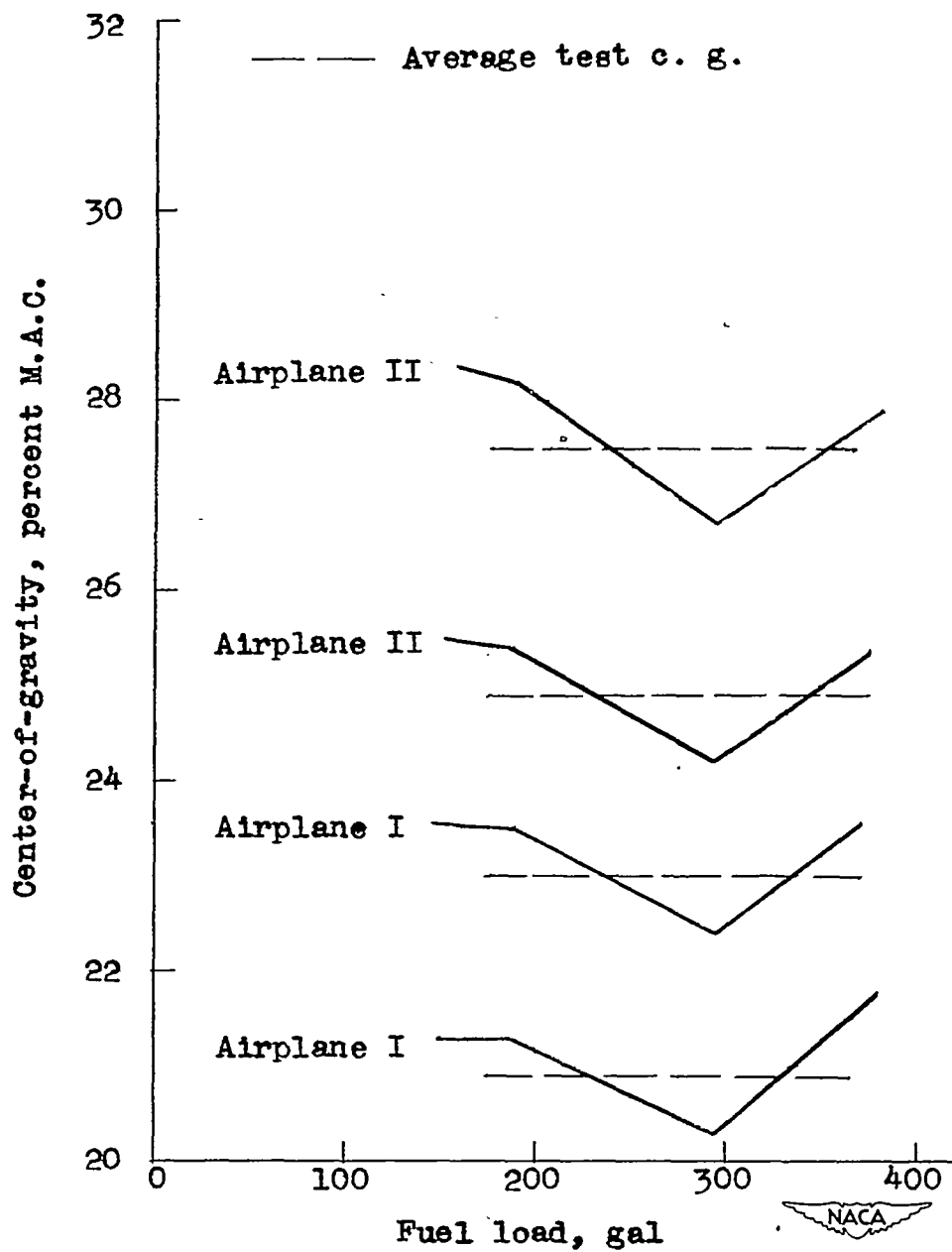


Figure 2.- Center-of-gravity travel with fuel load.

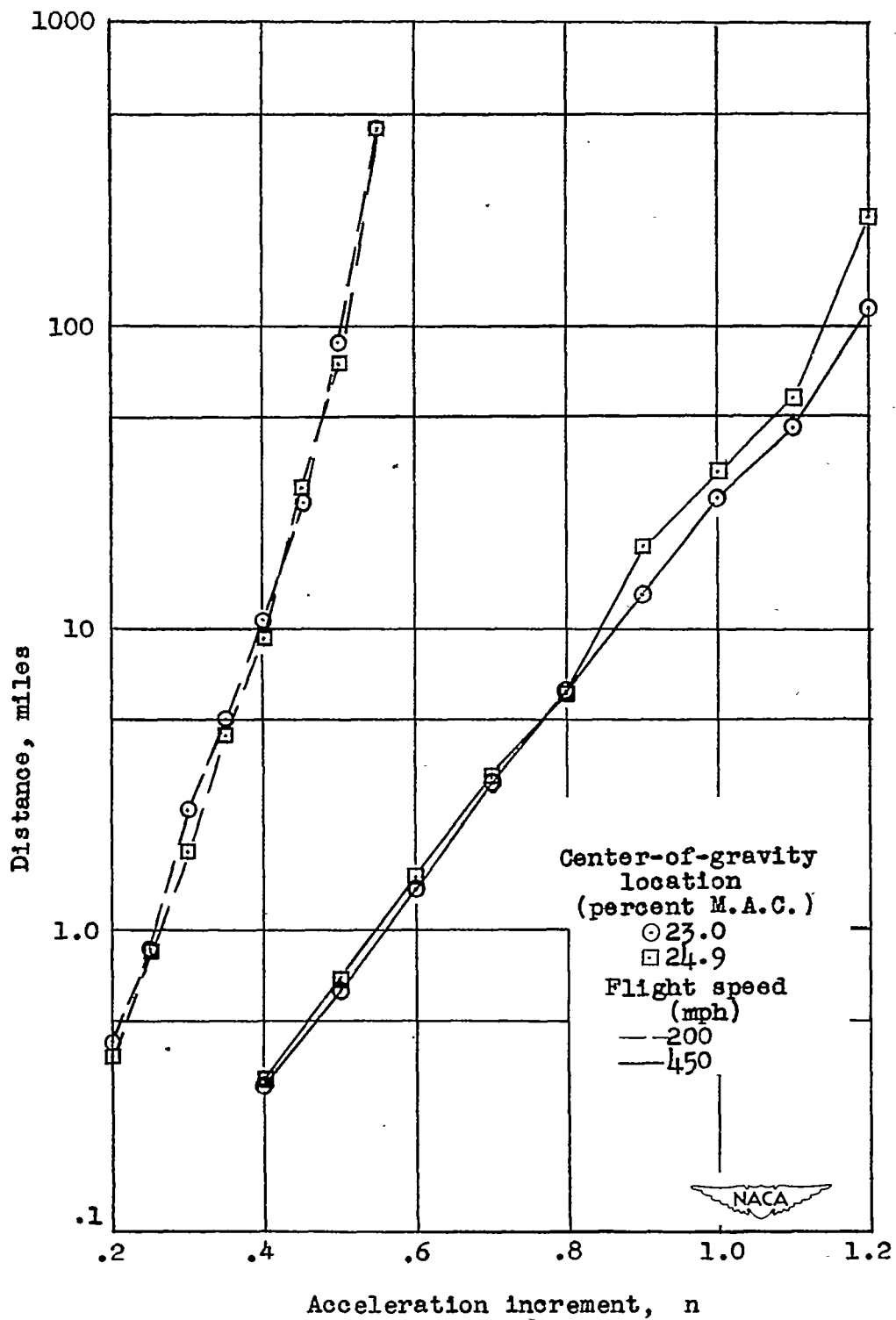


Figure 3.- Average number of miles flown to exceed a given acceleration for tests of airplanes I and II at nearly the same center-of-gravity location.

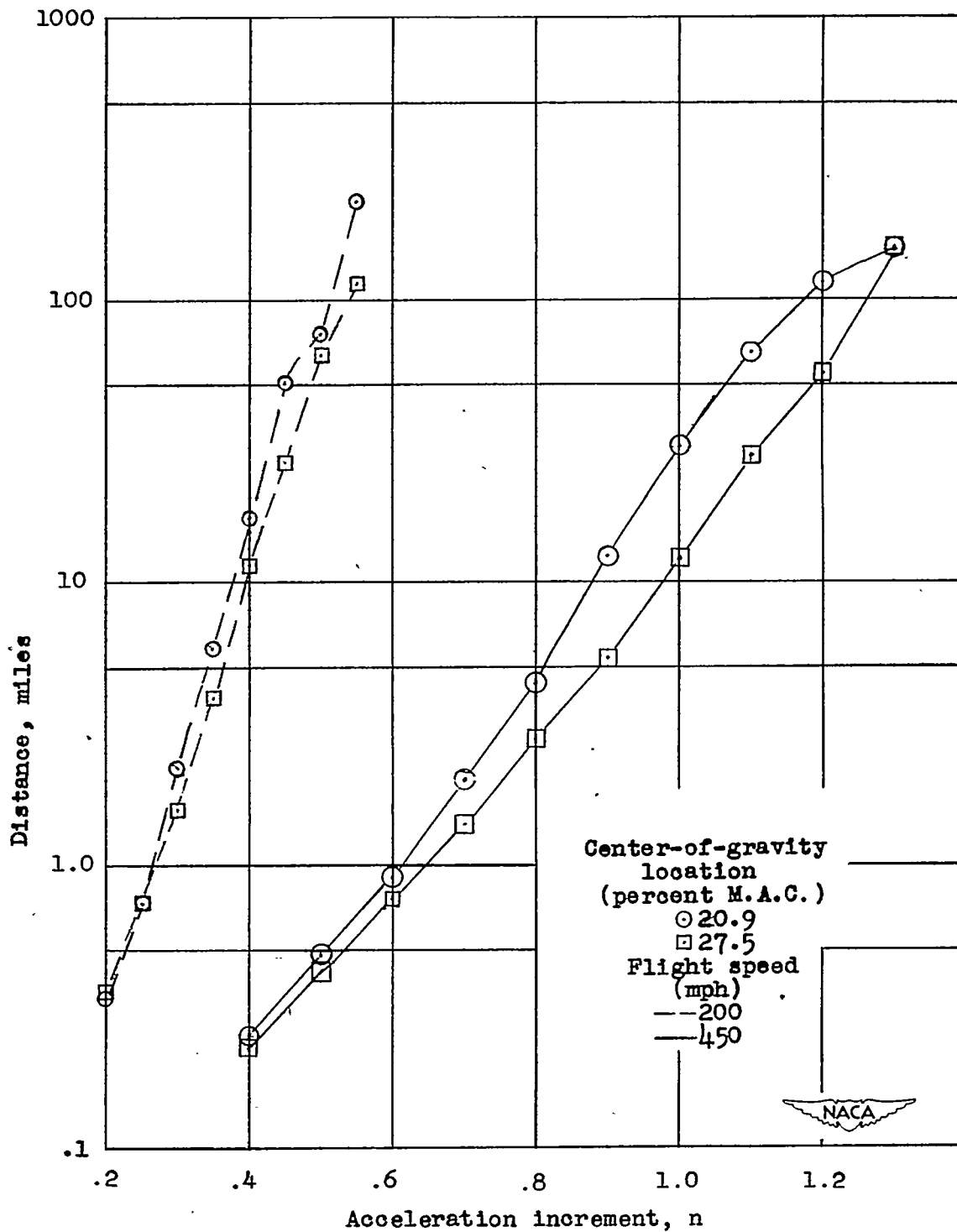


Figure 4.- Average number of miles flown to exceed a given acceleration for tests at different center-of-gravity locations.

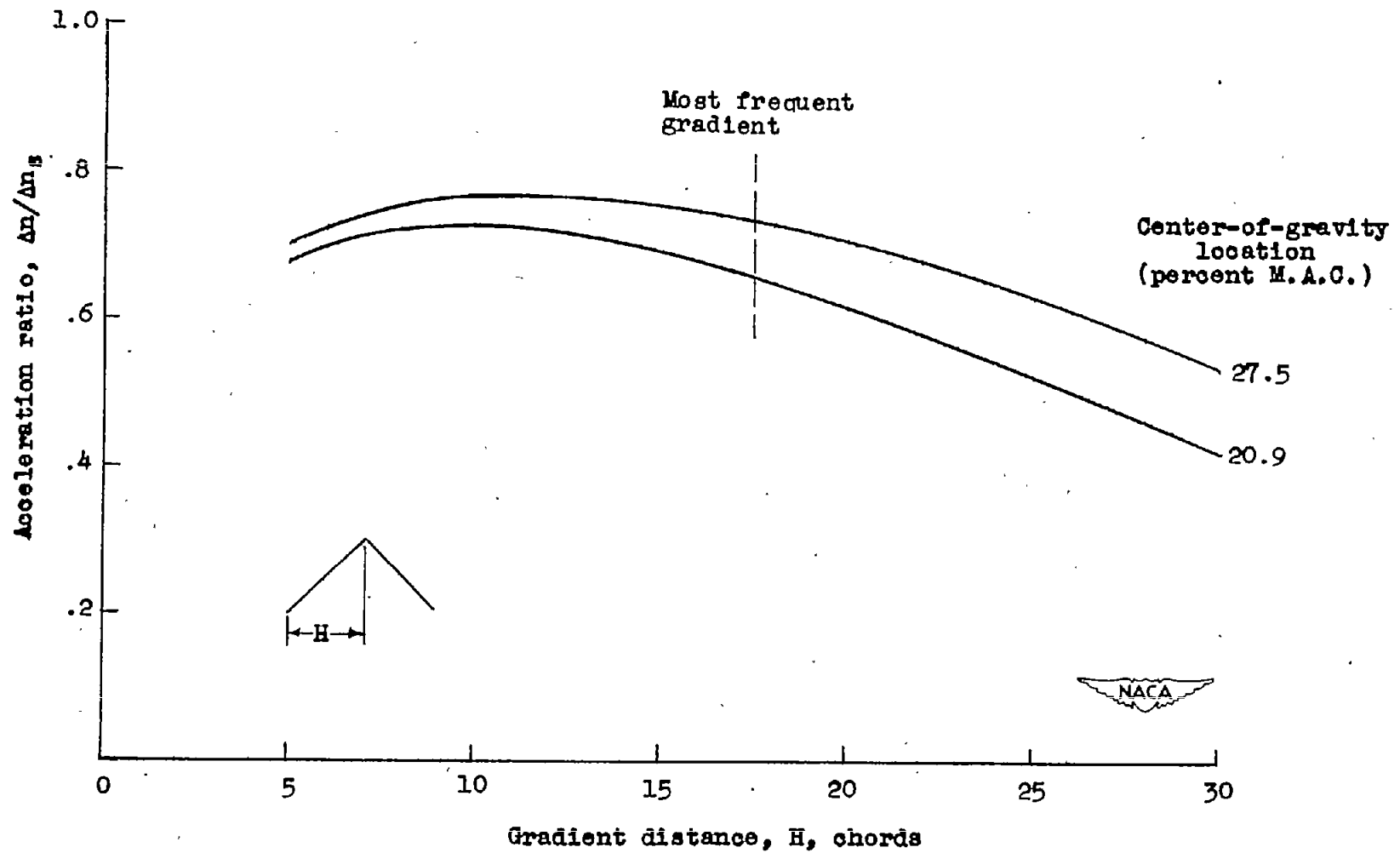


Figure 5.- Calculated acceleration ratios for triangular gust shapes for test airplanes.

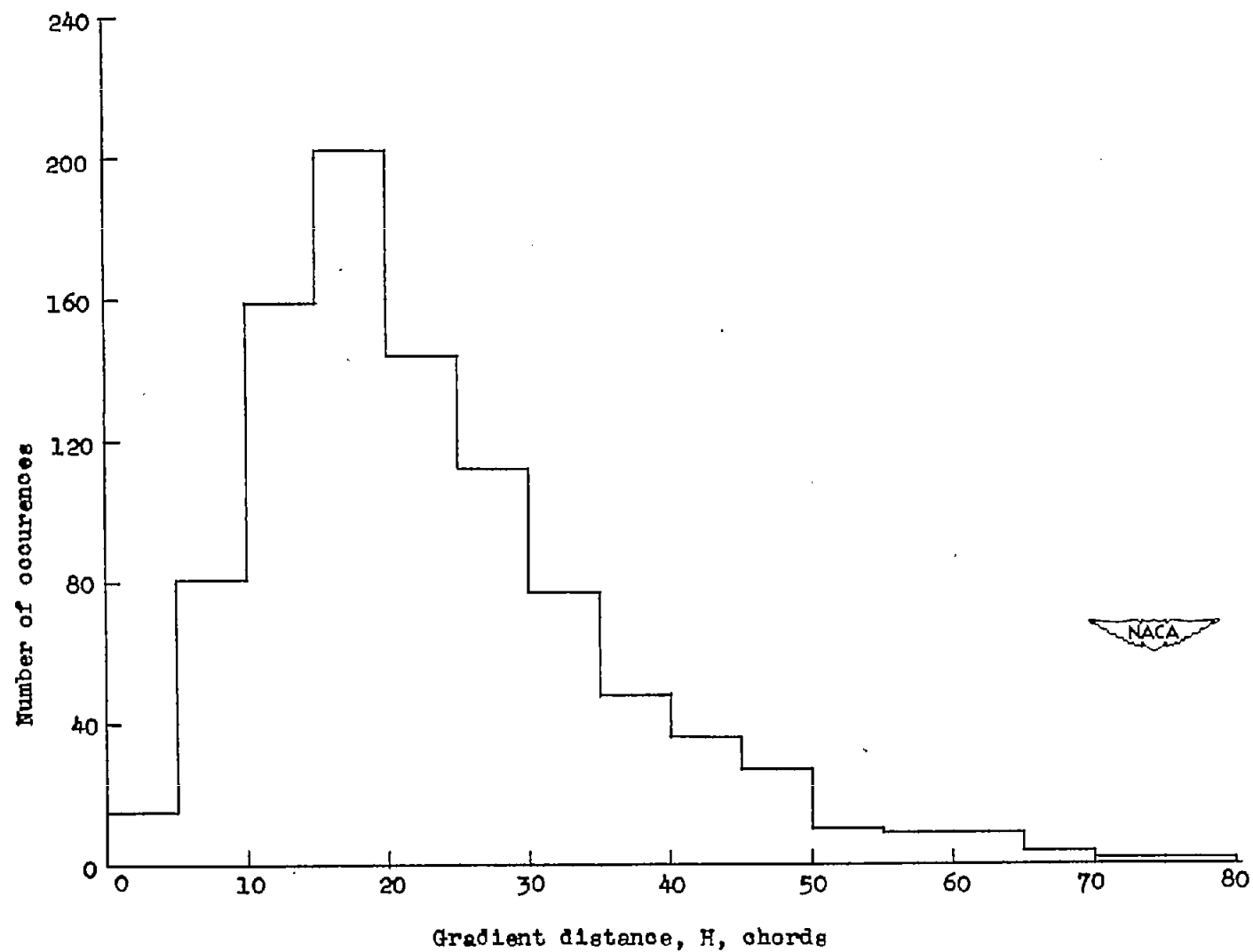


Figure 6.- Frequency distribution of gust gradient distances.